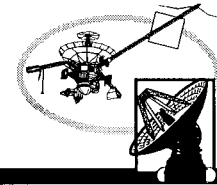**JPL**

Using DSP Technology
to Simplify Deep Space Ranging
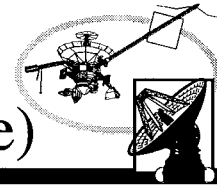
1999 Core Technologies
for Space Systems Conference
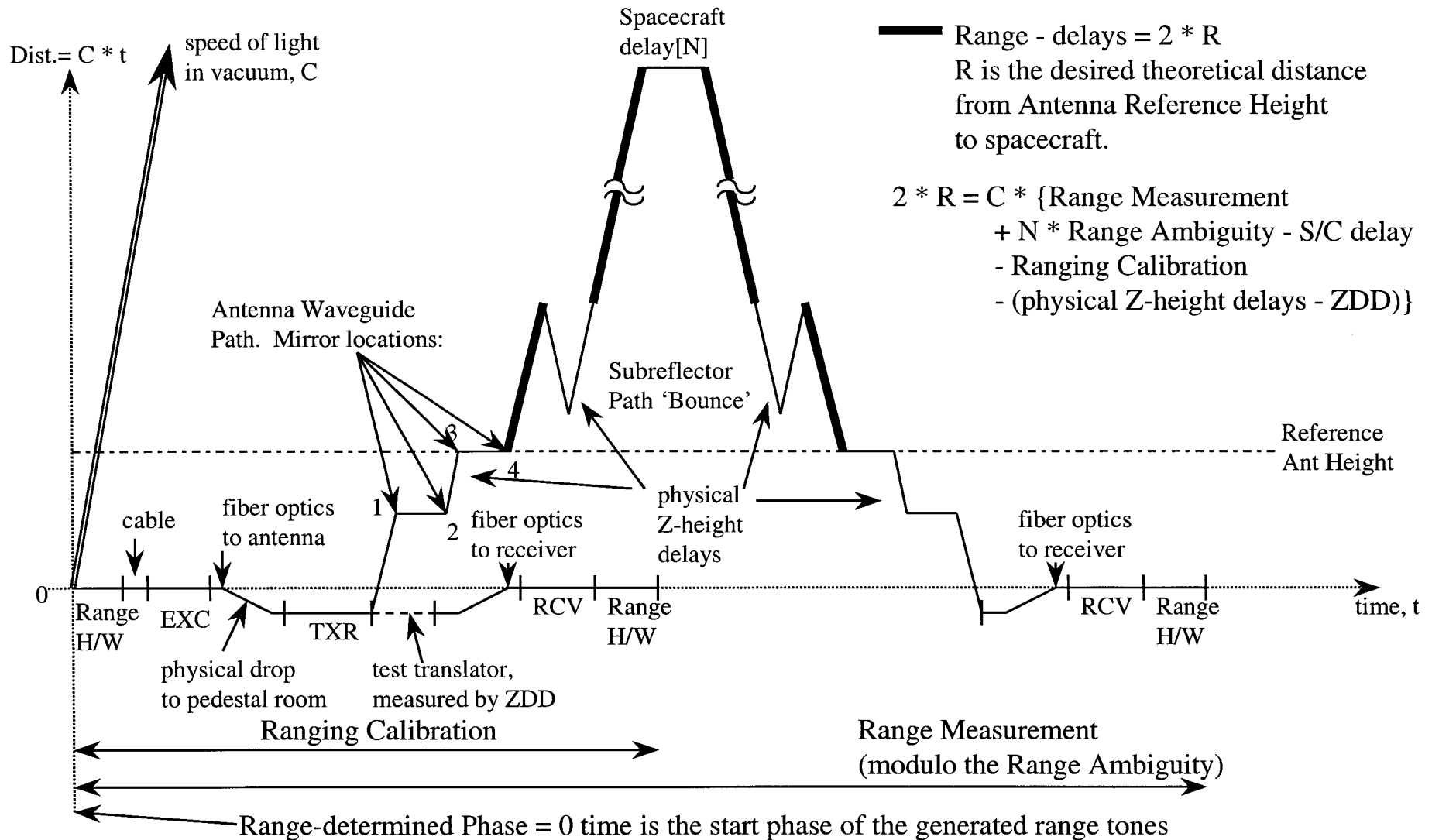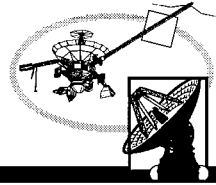
Scott Bryant
Jet Propulsion Laboratory

What is "Deep Space" Ranging?

- Provides a measurement of the distance from ground stations to a spacecraft under the following conditions:
  - Large distances. Anywhere from LEO (300 km) to Neptune (4.5 billion km).
  - Low signal. Down to -20 dB-Hz. But must also handle up to +50 dB-Hz.
  - Precise measurements. An actual measurement will depend on the ranging SNR, but the ranging system error sources RSS must be less than 1.25 m 1-sigma (1-way distance in meters).

- How are the ranging measurements used?
  - Spacecraft navigation teams use range to complement the doppler measurements. The spacecraft velocity implies an orbit location with error ellipses limited by carrier bandwidth. Range finds the absolute distance with an error ellipse based on signal strength. Using both increases orbit confidence. Range is crucial for:
    - Flybys, landings, and aerobraking.
    - Reduced tracking operations while in cruise mode.
  - Science teams study the media effects on range and doppler during planetary flybys to determine properties of the planet atmosphere. Similar studies are done for solar wind plasma studies.
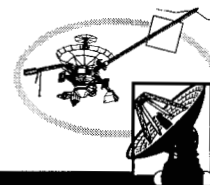
DSN Ranging as a time measurement (not to scale)

Range - delays = 2 * R
R is the desired theoretical distance
from Antenna Reference Height
to spacecraft.

Dist.= C * t

speed of light
in vacuum, C

Spacecraft
delay[N]

$2 * R = C * \{$Range Measurement
$\quad + N *$ Range Ambiguity - S/C delay
$\quad -$ Ranging Calibration
$\quad - ($physical Z-height delays - ZDD$)\}$

Antenna Waveguide
Path. Mirror locations:

Subreflector
Path 'Bounce'

3

4

Reference
Ant Height

cable

fiber optics
to antenna

1

2 fiber optics
to receiver

physical
Z-height
delays

fiber optics
to receiver

0

Range
H/W

EXC

TXR

RCV

Range
H/W

RCV

Range
H/W

time, t

physical drop
to pedestal room

test translator,
measured by ZDD

Ranging Calibration

Range Measurement
(modulo the Range Ambiguity)

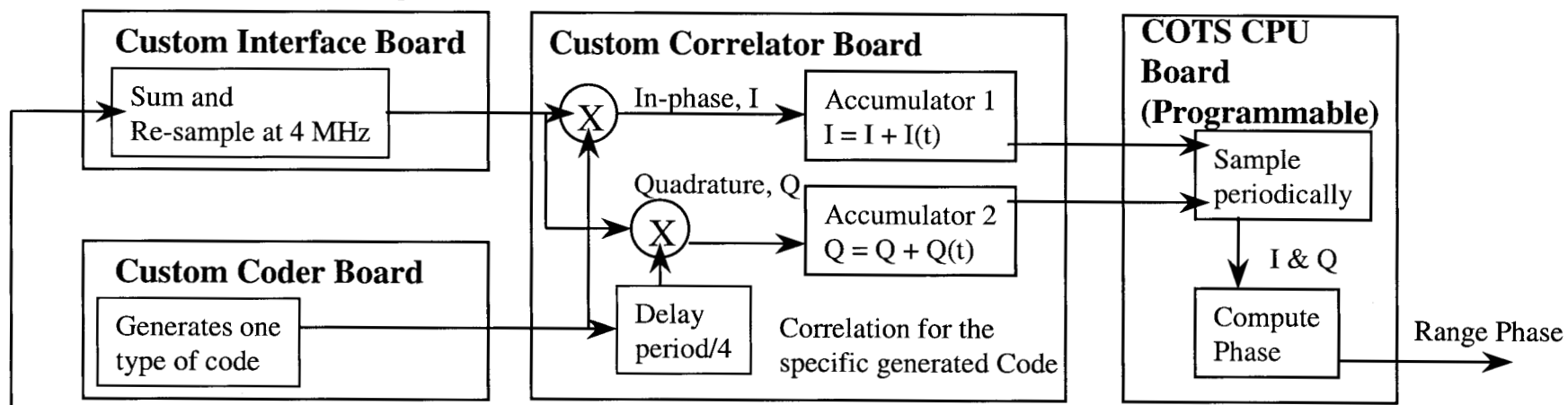Range-determined Phase = 0 time is the start phase of the generated range tones

SHB-3

How DSN Ranging Works

- The Ranging system actually measures a phase delay
  - The ranging H/W modulates a ranging pattern on the uplink carrier.
  - The spacecraft re-modulates the ranging pattern onto the downlink, but does not regenerate the signal. The ranging tone is coherent, but power goes as $1/R^4$.
  - The receiver removes the doppler shift from the received ranging tone.
  - The ranging H/W correlates the received pattern against a copy of the current uplink pattern being transmitted. The phase shift that maximizes the correlation is the phase delay introduced by the round trip light time traveled.

- Ranging H/W must provide the following functions:
  - The highest frequency ranging tone (clock tone) is 1 MHz. Lowest frequency tone is 1 KHz.
  - The received ranging pattern must be digitized at 4 MHz to get the quadrature.
  - The range measurement must be time tagged with 1.0 µsec accuracy.
  - The ranging system must support 2 types of ranging modulation.
    - A series of square-wave tones transmitted sequentially (supported by current DSN system)
    - Pseudo Noise codes modulated onto the clock frequency **(new requirement)**
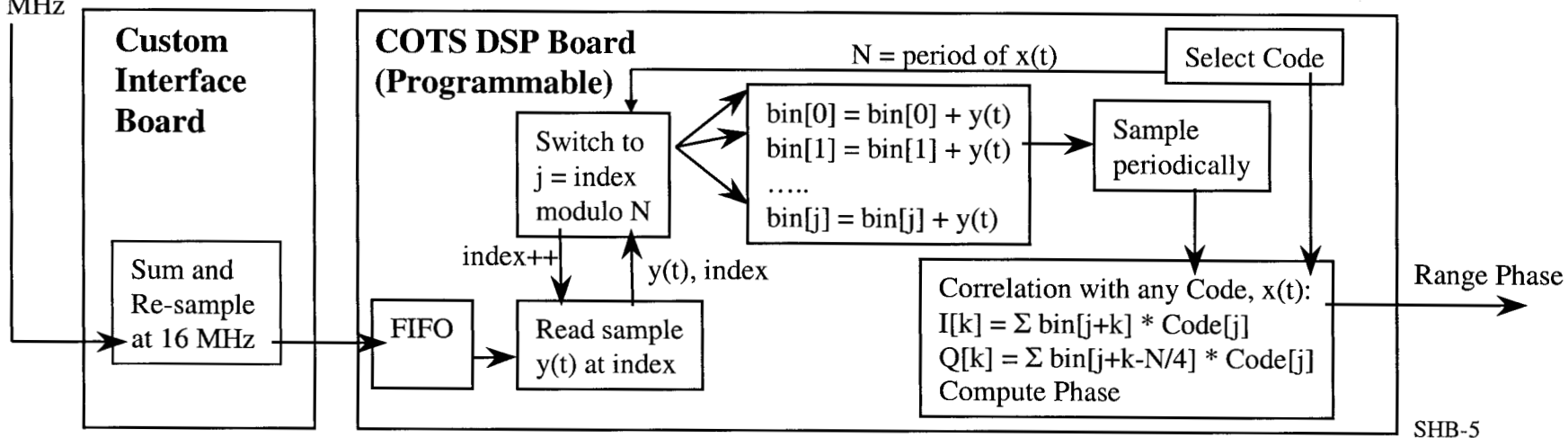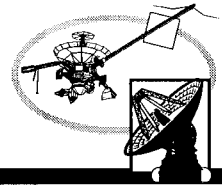
SHB-4

DSP technology enables new ranging design

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Old system: Code generation and Correlation in Hardware

Custom Interface Board

Sum and
Re-sample at 4 MHz

Custom Coder Board

Generates one
type of code

Custom Correlator Board

In-phase, I

$\times$

Quadrature, Q

$\times$

Delay
period/4

Correlation for the
specific generated Code

Accumulator 1
$I = I + I(t)$

Accumulator 2
$Q = Q + Q(t)$

**COTS CPU
Board
(Programmable)**

Sample
periodically

I & Q

Compute
Phase

Range Phase

Received Range signal,
$y(t) = x(t\text{-}RTLT) + noise(t)$
at 80 MHz

New system: Code generation and Correlation in Software

**Custom
Interface
Board**

Sum and
Re-sample
at 16 MHz

FIFO

Read sample
$y(t)$ at index

**COTS DSP Board
(Programmable)**

N = period of $x(t)$

Select Code

Switch to
j = index
modulo N

$bin[0] = bin[0] + y(t)$
$bin[1] = bin[1] + y(t)$
.....
$bin[j] = bin[j] + y(t)$

Sample
periodically

index++

$y(t)$, index

Correlation with any Code, $x(t)$:
$I[k] = \Sigma\ bin[j+k] * Code[j]$
$Q[k] = \Sigma\ bin[j+k\text{-}N/4] * Code[j]$
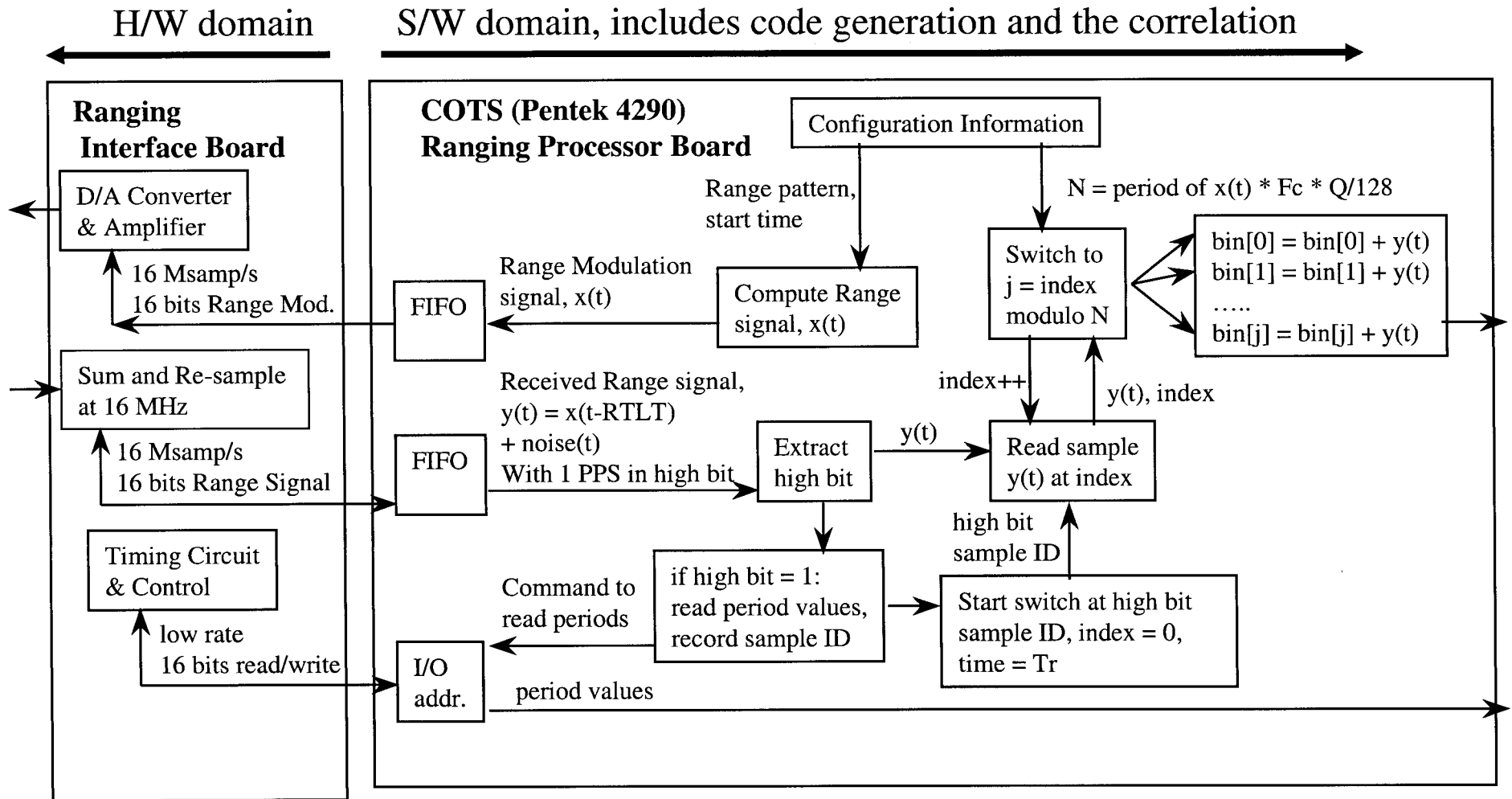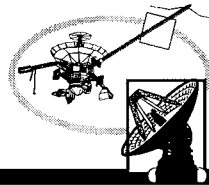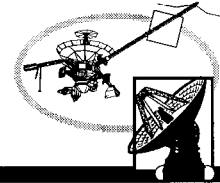Compute Phase

Range Phase

SHB-5

JPL

When did DSP technology catch up?

- The old ranging (the Sequential Ranging Assembly, SRA) is still working in the DSN. It was designed using late 1980's technology. You could not buy COTS processors that could handle 4 MHz FIFO inputs while also accumulating the samples in a bin.

- For the SRA design, it was cheaper to make custom correlators that could produce an I and Q for the processor to sample.

- JPL did a breadboard feasibility study in 1997-98 that proved that COTS DSPs approaching the 120 MHz processing speed could handle up to 16 MHz FIFO input.

- As part of the NASA and JPL's Network Simplification Project, the ranging functions will be consolidated into the receiver (1 pair of ranging boards) and the transmitter (1 pair of ranging boards) subsystems.

- The separate rack (2'x2'x6') dedicated to SRA and its controller will be replaced by 4 VME boards, 2 of which are COTS.

Design handles Uplink and Downlink Functions

JPL

H/W domain   S/W domain, includes code generation and the correlation

**Ranging
Interface Board**

D/A Converter
& Amplifier

↑ 16 Msamp/s
16 bits Range Mod.

Sum and Re-sample
at 16 MHz

↑ 16 Msamp/s
16 bits Range Signal

Timing Circuit
& Control

↑ low rate
16 bits read/write

**COTS (Pentek 4290)
Ranging Processor Board**

Configuration Information

Range pattern,
start time

$N = \text{period of } x(t) * Fc * Q/128$

Range Modulation
signal, x(t)

FIFO

Compute Range
signal, x(t)

Switch to
j = index
modulo N

bin[0] = bin[0] + y(t)
bin[1] = bin[1] + y(t)
.....
bin[j] = bin[j] + y(t)

Received Range signal,
$y(t) = x(t\text{-RTLT})$
+ noise(t)
With 1 PPS in high bit

FIFO

index++   y(t), index

Extract
high bit

y(t)

Read sample
y(t) at index

high bit
sample ID

Command to
read periods

if high bit = 1:
read period values,
record sample ID

Start switch at high bit
sample ID, index = 0,
time = Tr

I/O
addr.

period values

SHB-7

Advantages of New Ranging Design

- Less Custom H/W = Cheaper cost.

- Less H/W plus DSP boards that are smaller than older processor means less rack space, fewer spares, fewer cables, less cooling needs.

- The design puts the ranging code generation into the software. The new ranging system can be programmed to use any code modulated onto 1 MHz.
  - One set of H/W will support the old sequential tones and the PN tones.
  - PN needed to support new spacecraft transponders with regenerative ranging.

- DSP has 16 MHz FIFOs, providing for upgrade to 4 MHz range tones.

- DSP FIFOs and address for I/O control provide a very clean interface agreement between the COTS H/W and custom H/W.
  - Allows for future changes to one with changing the other.
  - Can upgrade to future DSP COTS products.

- DSP Boards are programmed in 'C' and have good development tools.

- Programmers can be found for DSP platforms, helping maintenance.
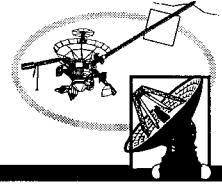
Some Prototype Results

- Tests used First Production Unit (FPU) H/W and prototyped S/W. H/W is:
  - Ranging Processor Board (RPB): Model 4290 quad TMS320C6201 processor DSP board from Pentek Inc. Includes Pentek Model 6227 mezzanine interface board.
  - Ranging Interface Board (RIB): JPL design, board produced by vendor.
  - RRP Interface Board: JPL design, board produced by vendor.
- Downlink demo at Demostration and Test Facility DTF-21:
  - Ran the SRA and new ranging (downlink only) in parallel.
    - Used the SRA for tone generation and input to exciter. Exciter output to 2 receivers
    - Configured both the SRA and the new ranging to receive inputs from different receivers.
  - Demo at DTF-21 proves:
    - Downlink H/W requirements are met by RPB, RIB, and RRP Interface Board.
    - RPB is fast enough for prototype S/W to keep up with samples, correlate the signal, and manage the RIB in realtime.
- Bldg 238 lab test validated uplink ranging H/W and RRP chassis compatibility.

# Test Results from DTF-21 downlink demo Oct. 1, 1999
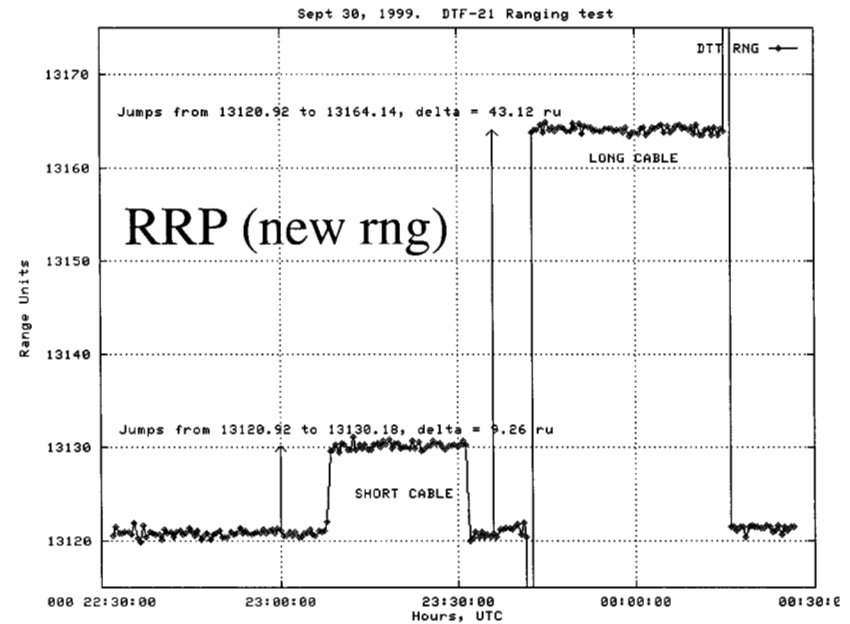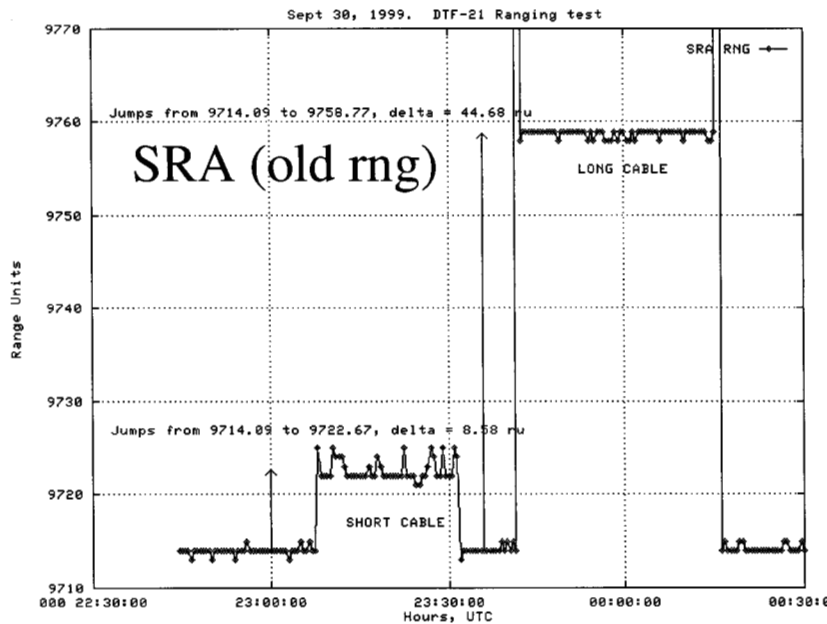
SRA and RRP ranging (downlink only) run simultaneously on the same SRA modulation output. The changes show increase in cable length relative to baseline:
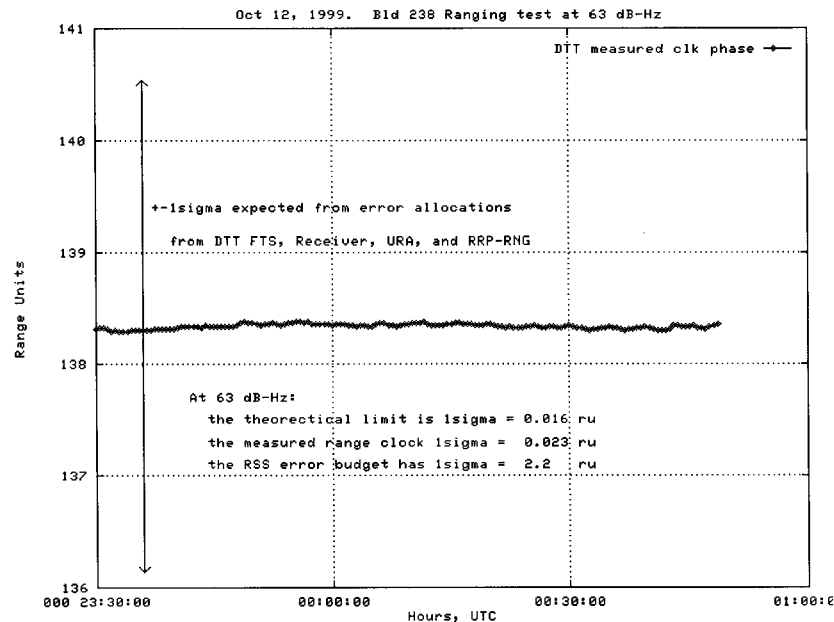
Cable	expected delay	SRA variance	RRP variance	[1 range unit ~ 1 nsec]
Short	9.1 range units	-0.5	0.2	
Long	42.1 range units	2.6	1.0	

SRA and RRP ranging measured the same ranging signal to noise density, 41 dB-Hz.

Hardware meets downlink baseband requirements.

SHB-10
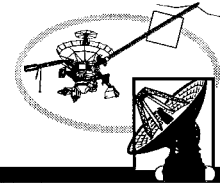
Test Results from bldg 238 lab. Oct. 12, 1999

Oct 12, 1999. Bld 238 Ranging test at 63 dB-Hz

Ranging test incorporated range boards into first-of-a-kind RRP. No problems were seen.
Test verified uplink ranging tone generation from FPU ranging hardware.
Ranging test done at 63 dB-Hz (higher than requirement) to discover the limitation from error sources in this configuration. The hardware is meeting (and exceeding) the requirement, in this configuration.